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Electrically Tunable Phase Shifters With Air-Dielectric Sandwich Structure

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ABSTRACT

Electrically tunable microwave phase shifter was developed by inserting dielectric slab and piezoelectric actuator inside a waveguide. Air-dielectric sandwich structure of dielectric material and thin air gap was placed inside a waveguide, where the thickness of air gap is controlled by the actuator. Small changes in the ratio between the thickness of dielectric material and air gap induce significant changes in the effective dielectric constant of the air-dielectric sandwich structure. Phase shifts of 20~200 degrees were realized with the dielectric materials such as (Mg, Ca)TiO_3 while the thickness of air gap is changed between 0 to 30 μm by piezoelectric control. Since the dielectric ceramics has very small loss ($\tan\delta \sim 10^{-4}$) and the air gap has practically no loss, the total structure shows low insertion loss.

INTRODUCTION

Microwave phase shifter is one of the essential components for modern microwave communication systems. One interesting application of the phase shifter is devoted to the phased array antenna, where the phase shifters located in one or two dimensional array with differential phase change provide fast steering of microwave signals. Commercial applications include global positioning system (GPS), car collision avoidance radar, aircraft surveillance radar and so on [1]. Development of electrically tunable phase shifters with low loss and low cost have been the key issue for determining the performance and cost of those microwave systems. Electrically tunable phase shifters using either ferrite or PIN diode have supported these microwave systems so far despite of severe disadvantages such as high cost and high insertion loss [2]. Moreover, they have fundamental frequency limitation of increasing loss in the millimeter-wave range where future communication systems may take place. Recently, ferroelectric phase shifters [3], micro-electro-mechanical systems (MEMS) phase shifters [4], and microstrip line phase shifters with piezoelectric control [5] have been studied, yet they are still far from practical applications.

We have developed a simple idea of realizing low loss phase shifter by combining well known conventional microwave dielectric ceramics and piezoelectric actuator [6]. As a high dielectric constant material is introduced inside a waveguide leaving a small air gap facing upper wall of the waveguide, the effective dielectric constant of the sandwich structure of dielectric material and air gap can be changed by controlling the thickness of air gap. Since the propagation constant of transmitting microwave changes as the effective dielectric constant of the sandwich structure changes, the structure can serve as a phase shifting element. We attached an electromechanical actuator in contact with dielectric material to control the air gap electrically in fast and accurate way.

THEORY AND EXPERIMENT

Let us consider a waveguide partially loaded with dielectric material as shown in figure 1. With this configuration, TE or TM modes cannot satisfy the boundary conditions any more. Rather the hybrid modes of them appear [7]. The propagation constant for the present configuration can be derived according to the equations,

$$\frac{\beta_{ya}}{\varepsilon_0}\tan(\beta_{ya}\Delta)+\frac{\beta_{yd}}{\varepsilon_d\varepsilon_0}(\beta_{yd}(b-\Delta))=0,$$

$$\beta_{ya}=\sqrt{\varpi^2\varepsilon_0\mu_0-\gamma^2-\beta_x^2},$$

$$\beta_{yd}=\sqrt{\varpi^2\varepsilon_d\varepsilon_0\mu_0-\gamma^2-\beta_x^2},$$

where β_{ya} is the transverse wave number in the air region, β_{yd} is the transverse wave number in the dielectric region, γ is the propagation constant, ε_d is the dielectric constant of dielectric material, Δ is the thickness of air gap, and b is the height of waveguide where dielectric material is placed. The solution can be obtained numerically. The effective dielectric constants of the air-dielectric sandwich structure for several different dielectric materials are shown in figure 2. The

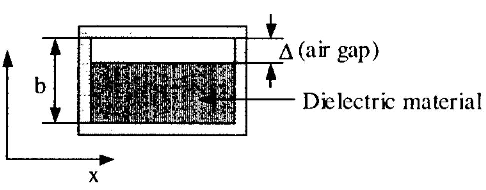

Figure 1. Cross section of the waveguide partially loaded with dielectric material.

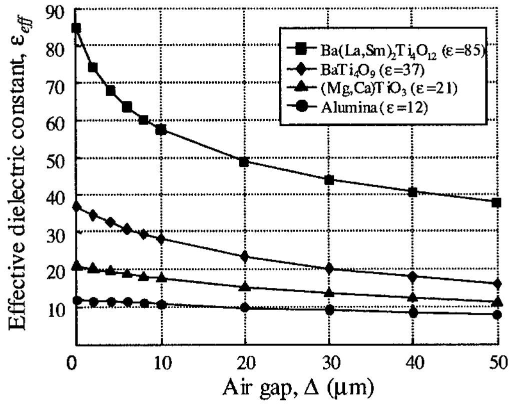

Figure 2. Effective dielectric constants of the air-dielectric sandwich structure for several different dielectric materials of 2 mm in the thickness.

effective dielectric constants decrease as the air gap is widened and such an effect is more significant for the materials with higher dielectric constants.

We devised a waveguide phase shifter in which the air-dielectric sandwich structure is constructed with a piezoelectric actuator to control the thickness of air gap electrically. As shown in figure 3, the air gap is controlled from 0 to 30 μm by applying voltage from 150 V down to –30V to the actuator. Scattering parameters were measured by HP 8510C Vector Network Analyzer. Simple matching sections with Teflon were provided before and after the dielectric materials to reduce reflection. The back side of the ceramic plate is covered by silver electrode, so the cavity where phase shift occurs is constructed.

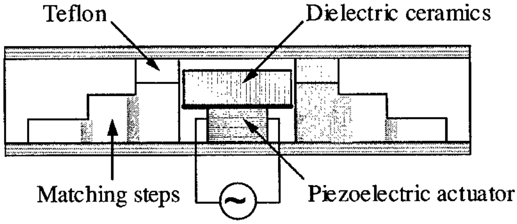

Figure 3. Side view of the waveguide loaded with an air-dielectric sandwich structure.

RESULTS

Experimental results of relative phase shift for the air-dielectric sandwich structure for different materials are shown in figure 4 and table I compares the results with the estimated values based on the results in figure 2. As the thickness of air gap is increased, noticeable phase change occurred depending on the dielectric materials. The effect of small air gap was more significant when the material with higher dielectric constant was used. Relative phase shift of 200 degrees was realized for $Ba(La,Sm)_2Ti_4O_{12}$ while 25 degrees for alumina. With a small variation in the thickness of air gap, materials with higher dielectric constant are preferred to induce large phase shift. However, it becomes difficult to match impedances for materials with very high dielectric constant, which results in severe reflection loss. Thus, there should be a compromise between high dielectric constant and ease of impedance matching.

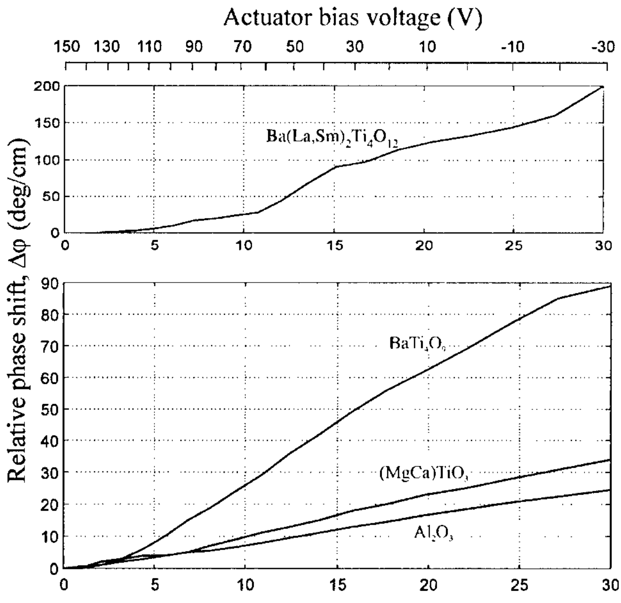

Figure 4. Relative phase shift for the air-dielectric sandwich structure with different dielectric materials measured at 10.5 GHz.

Table I. Comparison between the estimated phase shifts and the observed values with 10 mm dielectric slabs and 30 μm air gap.

Dielectrics	$\Delta\varphi$ expected (degree)	$\Delta\varphi$ observed (degree)
$Ba(La,Sm)_2Ti_4O_{12}$ ($\varepsilon = 85$)	311	200
$BaTi_4O_9$ ($\varepsilon = 37$)	83	89
$(Mg, Ca)TiO_3$ ($\varepsilon = 21$)	54	34
Alumina ($\varepsilon = 12$)	50	25

CONCLUSIONS

Electrically tunable microwave phase shifter was developed with the air-dielectric sandwich structure. We induced the phase shift by adjusting the thickness of air gap between waveguide wall and dielectric slab electrically by an electromechanical actuator inside a waveguide. It was possible to obtain 20~200 degrees of relative phase change depending on dielectric materials for the sample length of 10 mm. The present phase shifter seems to replace the conventional waveguide phase shifter with ferrite that is massive and expensive especially for phased array antennas. As we select the microwave ceramics with relatively low loss, it becomes possible to build low loss-phase shifters at the millimeter wave range, where commercial low loss phase shifters are non-existent.

ACKNOWLEDGEMENTS

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